Real-Time Performance Evaluation of a Genetic Algorithm Based Fuzzy Logic Controller for IPM Motor Drives

M. Nasir Uddin[1], *Member IEEE*, M. A. Abido[2], *Member IEEE*, and M. A. Rahman[3], *Fellow IEEE*

1. Department of Electrical Engineering
Lakehead University
Thunder Bay, Ontario P7B 5E1, Canada

2. Electrical Engineering Department
King Fahd University of Petroleum & Minerals
Dhahran, 31261, Saudi Arabia.

3. Faculty of Engg. & Appl. Science
Memorial University of Newfoundland
St. John's, Newfoundland A1B 3X5, Canada

Abstract-
This paper presents a novel speed control scheme using a genetic-based fuzzy logic controller (GFLC) for an interior permanent magnet synchronous motor (IPMSM) drive. The proposed GFLC is developed to have less computational burden, which makes it suitable for real-time implementation. The parameters for the GFLC are tuned by genetic algorithm (GA). The complete drive incorporating the GFLC is successfully implemented in real-time using a digital signal processor board DS 1102 for a laboratory 1 hp interior permanent magnet motor. The efficacy of the proposed GFLC based IPMSM drive is verified by simulation as well as experimental results at various operating conditions. A performance comparison with a conventional PI controller is also provided to show the superiority of the proposed controller. The proposed GFLC is found to be a robust for high performance industrial drive applications.

Index Terms- Interior Permanent Magnet Motor, Vector Control, Real-Time Implementation, Genetic Algorithm, Fuzzy Logic, and Digital Signal processor.

I. INTRODUCTION

The permanent magnet synchronous motor has recently become quite popular owing to its high torque to current ratio, large power to weight ratio, high efficiency, high power factor and robustness [1]. These features are due to the incorporation of high energy rare-earth alloys such as Neodymium-Iron-Boron magnets in its construction. Especially, the interior permanent magnet synchronous motor (IPMSM) which has magnets buried in the rotor core exhibit certain desirable properties, such as, mechanically robust rotor construction, a rotor physically non-saliency and small effective air gap. The rotors of these machines have a complex geometry to ensure optimal use of the expensive permanent magnet material while maintaining a high magnetic field in the air-gap. These features allow the IPMSM drive to be operated in high speed mode by incorporating the field weakening technique.

Usually, high performance motor drives used in robotics, rolling mills, machine tools, etc. require fast and accurate response, quick recovery from any disturbances and insensitivity to parameter variations. The dynamic behavior of an ac motor can be significantly improved using vector control theory where motor variables are transformed into an orthogonal set of d-q axes such that speed and torque can be controlled separately [2]. This gives the IPMSM machine the highly desirable dynamic performance capabilities of a separately excited dc machine, while retaining the general advantages of the ac over dc motors.

Traditionally, the control issues are handled by conventional proportional-integral (PI), proportional-integral-derivative (PID) controllers and various adaptive controllers such as model reference adaptive controller, sliding mode controller, variable structure controller, etc. However, the difficulties of obtaining the exact d-q axis reactance parameters of the IPMSM leads to cumbersome design approach for these controllers. Furthermore, the conventional fixed gain PI and PID controllers are very sensitive to step change of command speed, parameter variations and load disturbance [3]. Again, precise speed control of an IPMSM drive becomes a complex issue due to nonlinear coupling among its winding currents and the rotor speed as well as the nonlinearity presents in the electromagnetic developed torque due to magnetic saturation of the rotor core [4]. Because of these nonlinear natures of IPMSM, an intelligent controller demands special attention for precise speed control of high performance drive systems. To serve that purpose, a simple and new type of fuzzy logic controller (FLC) is developed in the present work.

The mathematical tool for FLC is the fuzzy set theory introduced by Zadeh [5]. In recent years, some efforts have been made on the use of fuzzy algorithms for system modeling and control applications [6-12]. In a fuzzy logic controller (FLC), the system control parameters are adjusted by a fuzzy rule based system, which is a logical model of the human behavior for process control. The main advantages of FLC over the conventional controllers are that the design of FLC does not need the exact mathematical model of the system and it can handle nonlinear functions of arbitrary complexity. Some work has been reported recently on the application of FLC for brushless dc, induction, IPMSM and reluctance motors [8-12]. However, the real-time application of conventional FLC with multiple inputs having multiple membership functions and multiple rules has been facing some disadvantages due to its high computational burden [13]. That is why so far the reported works for motor drives [10,11] are based on the simulation results only and some [3,8,9,12] are experimental with poor performance. Thus, there is a strong need for successful development and real-time implementation of fuzzy logic algorithms, which will be suitable for practical industrial drives. Hence the main issue of this paper is to develop and implement a new FLC for IPMSM drive in real-time, which overcomes the high computational burden and can handle nonlinear nature of IPMSM. Reference [12] presented a real-time implementation of a FLC for IPMSM. However, in that work the FLC was a complex one with too many membership functions and hence the maximum attainable sampling frequency was limited to 5 kHz. In the present work, the developed FLC is simple, effective and more suitable for real-time implementation, as it has only one membership function for each of the two inputs and the output variable does not have any membership function. Therefore, the obtained sampling frequency is 10 kHz. Moreover, GA is used to tune the parameters of the FLC, which is a more scientific way than the trial and error procedures used in [12].

The objective of this paper is to develop and implement a genetic based fuzzy logic controller (GFLC) for the interior permanent magnet ac motor drive. A GFLC for the IPMSM drive is designed and successfully implemented in real-time using digital signal processor board DS-1102. The performance of the proposed GFLC based IPMSM drive is investigated both in simulation and experiment at different dynamic operating conditions. In order to verify the superiority of the proposed controller a performance comparison with a conventional PI controller is also provided.

II. IPMSM DRIVE MODEL

The mathematical model of an IPMSM drive can be described by the following equations in a synchronously rotating rotor d-q reference frame as [12]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -P\omega_r L_q \\ P\omega_r L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ P\omega_r \psi_f \end{bmatrix} \quad (1)$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \quad (2)$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q + (L_d - L_q) i_d i_q\right) \quad (3)$$

where, v_d, v_q = d- and q-axis stator voltages;

i_d, i_q = d- and q-axis stator currents;

R = stator per phase resistance;

L_d, L_q = d- and q-axis stator inductances;

T_e, T_L = electromagnetic and load torques;

J_m = moment of inertia of the motor and load;

B_m = friction coefficient of the motor;

P = number of poles of the motor;

ω_r = rotor speed in angular frequency;

p = differential operator (=d/dt);

ψ_f = rotor magnetic flux linking the stator.

It is well known that a synchronous motor is unable to self-start when supplied with a constant frequency source. The starting torque in the IPMSM drive used in this research is provided by a rotor squirrel cage winding. The starting process of the IPMSM drive can be considered as a superposition of two operating modes, namely, unsymmetrical asynchronous motor mode and magnet-excited asynchronous generator mode. Therefore, the effect of shorted rotor windings has to be considered, if one wants to examine the process of run-up to the synchronization. However, the model equations in (1) to (3) do not describe the asynchronous behavior of the IPMSM drive.

III. CONTROL PRINCIPLE

The objective of this paper is to obtain the IPMSM control voltages in order to achieve high performance speed tracking. According to the motor model given in equations (1-3), it can be seen that the speed control can be achieved by controlling the d-q-axis component of the current. For the sake of testing the proposed new technique, the speed control over the normal mode of operation can be achieved by controlling the q-axis component i_q of the supply current as long as the d-axis current i_d is maintained at zero. The resultant IPMSM model can be represented as,

$$pi_q = \frac{1}{L_q}\left(v_q - Ri_q - P\omega_r \psi_f\right) \quad (4)$$

$$v_d = -\omega_r L_q i_q \quad (5)$$

$$T_e = T_L + J_m p\omega_r + B_m \omega_r \quad (6)$$

$$T_e = \frac{3P}{2}\left(\psi_f i_q\right) \quad (7)$$

The machine parameters are given in Table-I. In the following subsections, the FLC and the GA used for tuning of the FLC parameters are explained.

Table-I: Machine parameters

Motor rated power	3-phase, 1 hp
Rated voltage	208 V
Rated current	3 A
Rated frequency	60 Hz
Pole pair number (P)	2
d-axis inductance, L_d	42.44 mH
q-axis inductance, L_q	79.57 mH
Stator resistance, R	1.93 Ω
Motor inertia, J_m	0.003 kgm^2
Friction coefficient, B_m	0.001 Nm/rad/sec
Magnetic flux constant, ψ_f	0.311 volts/rad/sec

A. FLC Scheme

The block diagram of a GFLC based vector control of IPMSM drive is shown in Fig.1. In this figure i_q^* is the control output, which can be defined as,

$$i_q^*(k) = i_q^*(k-1) + U(k) \quad (8)$$

At time t, $u(t)$ is given by,

$$u(t) = U(k) \quad ; kT_s < t < (k+1)T_s \quad (9)$$

The value of $U(k)$ is determined at each sampling time based on fuzzy logic through the following steps [13]:

Step 1: The speed deviation, $\Delta\omega(k)$, is measured at every sampling time, and the acceleration of the machine, $A(k)$, is calculated as follows,

$$A(k) = [\ \Delta\omega(k) - \Delta\omega(k-1)\ ] / T_s \quad (9)$$

Step 2: Compute the scaled acceleration, $A_s(k)$, using

$$A_s(k) = A(k)^*F_a \quad (10)$$

Step 3: The motor operating condition as shown in Fig.2 is given by the point $C(k)$ where

$$C(k) = (\ \Delta\omega(k)\ ,\ A_s(k)\ ) \quad (11)$$

Step 4: Calculate $R(k)$ and $\theta(k)$ using

$$R(k) = |\ C(k)\ | \quad (12)$$

and, $\theta(k) = \tan^{-1}(\ A_s(k)\ /\ \Delta\omega(k)\ )$ (13)

Step 5: Compute the values of membership functions $N_s(\theta)$ and $P_s(\theta)$,defined as shown in Fig.3(a),

$$N_s(\theta) = \begin{cases} 1 & 0 \le \theta \le \pi/2 \\ 2(\pi - \theta)/\pi & \pi/2 < \theta \le \pi \\ 0 & \pi < \theta \le 3\pi/2 \\ 2(\theta - 3\pi/2)/\pi & 3\pi/2 < \theta \le 2\pi \end{cases} \quad (14)$$

$$P_s(\theta) = \begin{cases} 0 & 0 \le \theta \le \pi/2 \\ 2(\theta - \pi/2)/\pi & \pi/2 < \theta \le \pi \\ 1 & \pi < \theta \le 3\pi/2 \\ 2(2\pi - \theta)/\pi & 3\pi/2 < \theta \le 2\pi \end{cases} \quad (15)$$

Step 6: Determine the value of the gain function $G_c(k)$ defined as shown in Fig. 3(b),

$$G_c(k) = \begin{cases} R(k)\ /\ D_r & \forall R(k) \le D_r \\ 1.0 & \forall R(k) > D_r \end{cases} \quad (16)$$

Step 7: Compute the stabilizing signal $U(k)$ using

$$U(k) = G_c(k)\ [\ P_s(\theta) - N_s(\theta)\ ]\ U_{max} \quad (17)$$

Step 8: Increase k by 1 and return to step 1.

The main tuning parameters of the proposed GFLC are U_{max}, F_a, and D_r. For the optimal settings of these parameters, following quadratic performance index J is considered:

$$J = \sum_{k=1}^{L} [kT_s \Delta\omega(k)]^2 \quad (18)$$

In the above index, the speed deviation $\Delta\omega(k)$ is weighted by the respective time kT_s. The index J is selected because it reflects small settling time, small steady state error, and small overshoots. The tuning parameters are adjusted so as to minimize the index J.

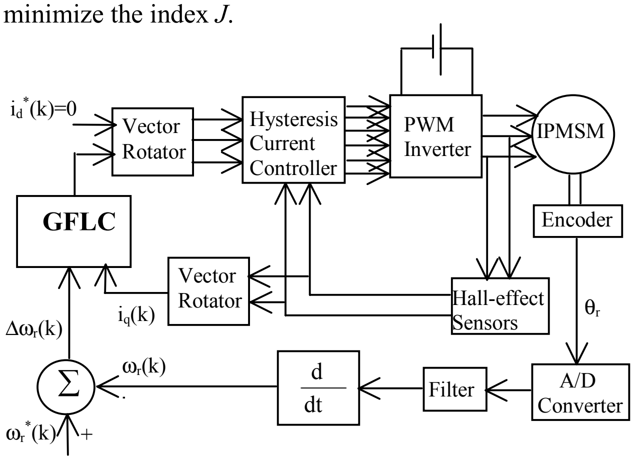

Fig.1 Block diagram of the proposed GFLC based IPMSM drive.

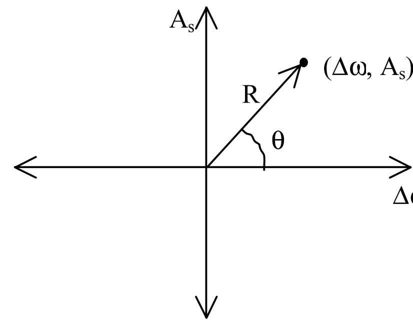

Fig.2. The motor operating point.

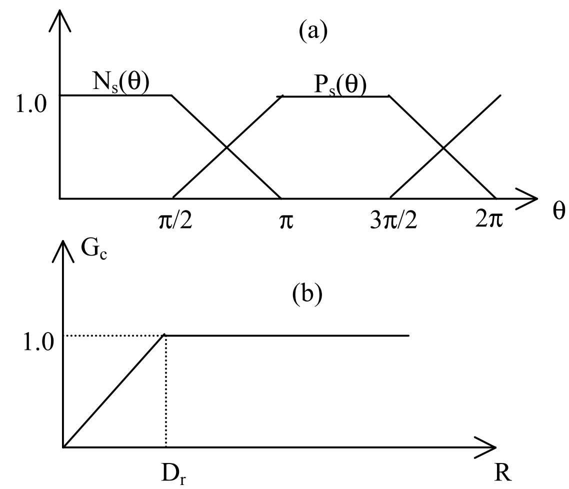

Fig.3. Membership functions for:, (a) θ, and (b) R.

B. Genetic Algorithms:

Genetic algorithms are exploratory search and optimization procedures that were devised on the principles of natural evolution and population genetics [14]. Unlike other optimization techniques, GA work with a population of individuals represented by bit strings and modify the population with random search and competition. Typically, the GA starts with little or no knowledge of the correct solution depending entirely on responses from interacting environment and their evolution operators to arrive at optimal or near optimal solutions. In general, GA include operations such as reproduction, crossover, and mutation. Reproduction is a process in which a new generation of population is formed by selecting the fittest individuals in the current population. Crossover is the most dominant operator in GA. It is responsible for producing new offsprings by selecting two strings and exchanging portions of their structures. The new offsprings may replace the weaker individuals in the population. Mutation is a local operator, which is applied with a very low probability. Its function is to alter the value of a random position in a string.

B.1. Real-Coded Genetic Algorithm (RCGA)

Due to difficulties of binary representation when dealing with continuous search space with large dimension, the proposed approach has been implemented using real-coded genetic algorithm (RCGA). A decision variable x_i is represented by a real number within its lower limit a_i and upper limit b_i, i.e. $x_i \in [a_i,b_i]$.

The RCGA crossover and mutation operators are described as follows:

Crossover**:** A blend crossover operator has been employed in this study. This operator starts by choosing randomly a number from the interval $[x_i - \alpha(y_i - x_i), y_i + \alpha(y_i - x_i)]$, where x_i and y_i are the i^{th} parameter values of the parent solutions and $x_i < y_i$. To ensure the balance between exploitation and exploration of the search space, $\alpha = 0.5$ is selected.

Mutation**:** The non-uniform mutation operator has been employed in this study. The new value x_i' of the parameter x_i after mutation at generation t is given as

$$x_i' = \begin{cases} x_i + \Delta(t, b_i - x_i) & \text{if } \tau = 0 \\ x_i - \Delta(t, x_i - a_i) & \text{if } \tau = 1 \end{cases} \tag{19}$$

and;

$$\Delta(t, y) = y(1 - r^{(1-\frac{t}{g_{\max}})^{\beta}}) \tag{20}$$

where τ is a binary random number, r is a random number $r \in [0,1]$, g_{max} is the maximum number of generations, and β is a positive constant chosen arbitrarily. In this study, $\beta = 5$ was selected. This operator gives a value $x_i' \in [a_i,b_i]$ such that the probability of returning a value close to x_i increases as the algorithm advances. This makes uniform search in the initial stages and very locally at the later stages.

B.2. The Computational Flow

Applying GA to the problem of FLC design involves repetitively performing the following two basic steps.

1. The objective function value must be calculated for each of the strings in the current population.
2. GA operations are applied to produce the next generation of the strings.

These steps are repeated until the population has converged. The computational flow of the problem can be shown in Fig. 4. In this work the optimal parameters of the proposed GFLC are found as follows: $U_{max} = 3$, $D_r = 10$, $F_a = 7$.

IV. REAL-TIME IMPLEMENTATION

The proposed GFLC for IPMSM is experimentally implemented using digital signal processor (DSP) board DS1102 through both hardware and software [15]. The detailed hardware schematic for real-time implementation of the proposed drive is given in reference [3]. The actual motor currents are measured by the Hall-effect sensors and fed to the DSP board through A/D converter. The rotor position is measured by an optical incremental encoder which is mounted

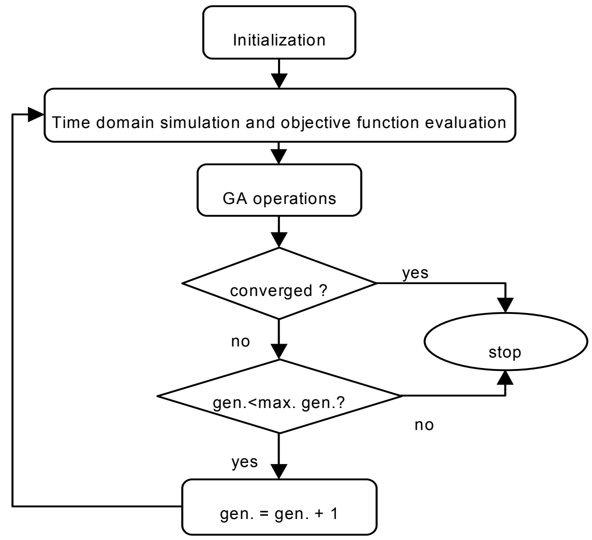

Fig.4. Computational flow chart for GA.

at the rotor shaft end. Then it fed to the DSP board through the encoder interface.

The motor speed is calculated from the rotor position by backward difference interpolation. The calculated actual motor speed is used to calculate the torque component of the command current i_q^* using the GFLC algorithm. The command a-b-c phase currents are generated from i_q^* using inverse Park's transformation [12]. In order to implement the vector control algorithm, the hysteresis controller is used as current controllers. The hysteresis current controller compares the command currents with the corresponding actual motor currents and generates the logic signals, which act as firing pulses for the inverter switches. Thus, these six PWM logic signals are the output of the DSP board and fed to the base drive circuit of the inverter power module. The D/A channels are used to capture the necessary output signals in digital storage oscilloscope.

The complete IPMSM drive is implemented through software by developing a program in high level 'C' programming language. The program is compiled by the TI 'C' compiler and then the program is downloaded to the DSP controller board. The sampling frequency for experimental implementation of the proposed IPMSM drive system is 10 kHz.

V. RESULTS AND DISCUSSION

In order to establish the effectiveness of the proposed GFLC scheme, the performance of the IPMSM drive based on the proposed control scheme is investigated both in simulation and experiment at different operating conditions. The speed control loop of the drive was also designed, simulated and experimentally implemented with PI controller, in order to compare the performances to those obtained from the respective GFLC based drive system. Sample results are presented below. The complete drive has been simulated using Matlab/Simulink [16].

In order to make a fair comparison the PI controller is tuned at rated conditions. The simulated responses of the drive are shown in Figs. 5 and 6 for PI and GFLC, respectively, to see the starting performance as well as the response with a load disturbance. The drive system is started at a constant load of 1 Nm with the speed reference set at 1800 rpm (188.5 rad/sec). It is seen from Fig. 6(a) that the GFLC based drive can follow the command speed within 0.1 second without any overshoot, undershoot and steady-state error. Whereas, Fig. 5(a) shows that the PI controller suffers from a big overshoot and takes a long time to reach the steady-state. At t=0.3 seconds, a load torque of 2 Nm is applied to the motor shaft in a stepwise manner. Also in this case the GFLC based drive system shows the superiority over PI as the actual speed does not change during the load disturbance while the stator current swiftly reaches to its new value corresponding to the load applied. Another simulated speed responses of the drive for a sudden change in command speed are shown in Figs. 7(a) & 7(b) for PI and GFLC, respectively. It is evident from Fig. 7(b) that the proposed GFLC based IPMSM drive system can follow the command speed quickly without any overshoot and steady state error. So the GFLC based drive system is not affected by the sudden change in command speed. Thus, a good speed tracking has been achieved for the GFLC. Whereas, the PI controller based drive system is affected with the sudden change in command speed.

The simulated results are verified by the experimental results. Figures 8(a) and 8(b) show the experimental starting speed responses of the drive system using PI and GFLC, respectively. It is to be noted that the genetic based fuzzy controller gives better responses in terms of overshoot, steady state vibration and fast response. The experimental speed responses with step increase in load are shown in Figs. 9 and 10 for the conventional PI and the proposed GFLC based IPMSM drive system, respectively. These figures also show that the GFLC based drive system is superior to PI based system in terms of insensitiveness to load disturbance. Figures 11(a) and 11(b) show the experimental speed responses with step change in command speed for the conventional PI and the proposed GFLC based drive, respectively. These figures also show that the GFLC based drive system can handle the sudden change in command speed quickly without overshoot, undershoot and stead-state error, whereas the PI controller based drive system has an overshoot only for a step increase of 30 rad./sec. and the response is not as faster as compared to the GFLC. Thus, the proposed GFLC based drive has been found superior to the conventional PI controller based system and hence a robust controller for high performance industrial drive applications.

V. CONCLUSIONS

The proposed GFLC based vector control of IPMSM drive has been successfully implemented in real-time for a laboratory 1 hp interior type permanent magnet motor. The

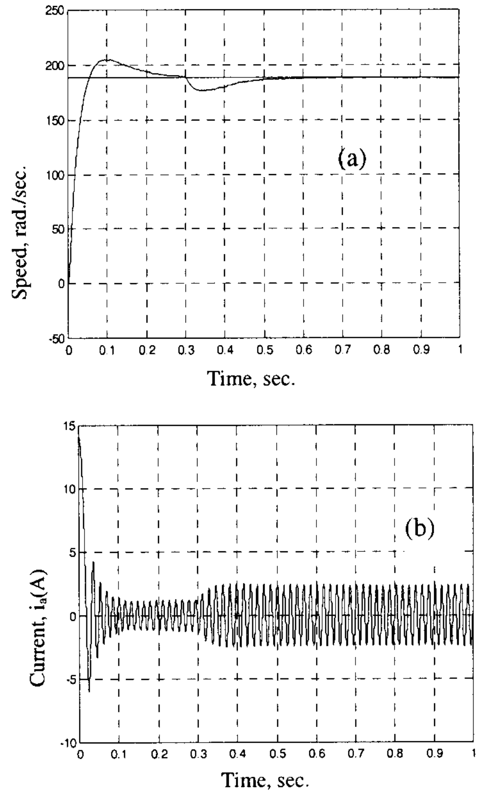

Fig.5 Simulated starting responses of the drive with PI: (a) speed and, (b) current, i_a.

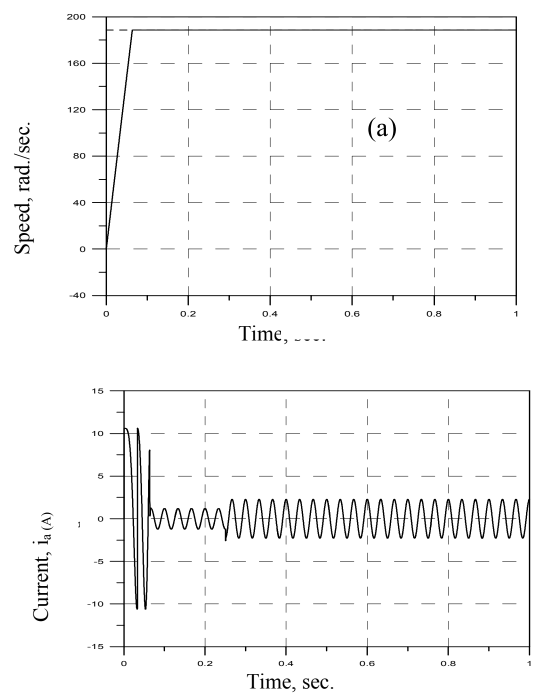

Fig.6 Simulated starting responses of the drive with GFLC: (a) speed and, (b) current, i_a.

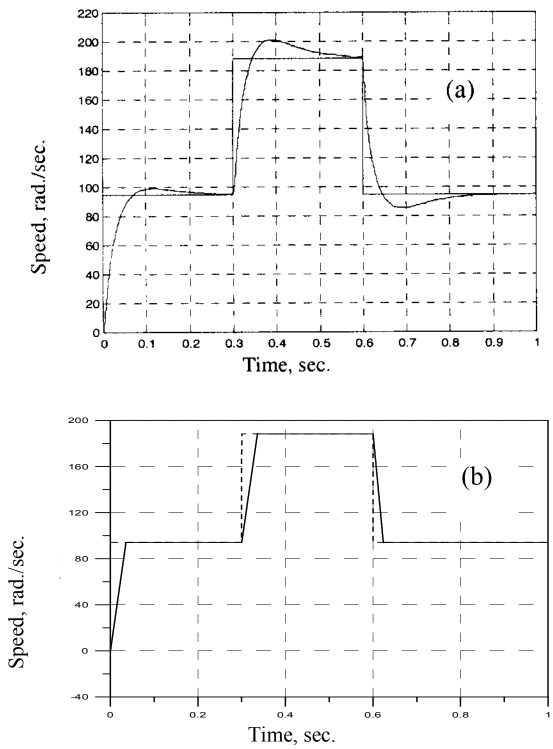

Fig.7 Simulated speed responses of the drive for a sudden change in speed: (a) PI, (b) GFLC.

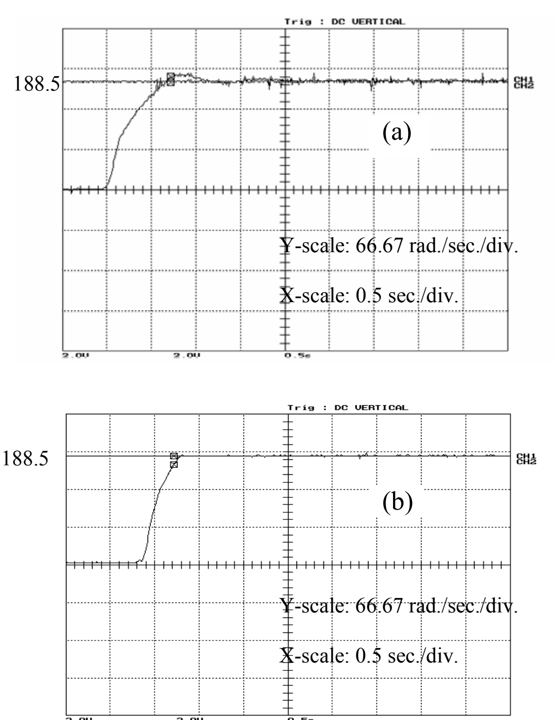

Fig.8 Experimental starting responses of the drive for: (a) PI, (b) GFLC.

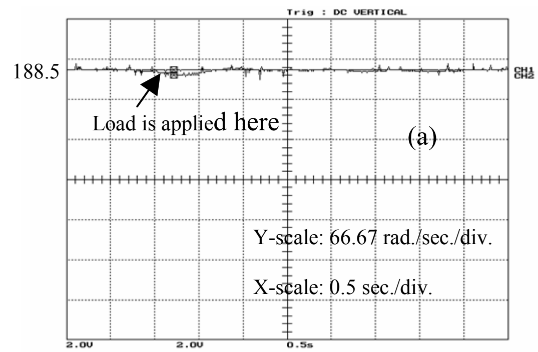

Fig.9 Experimental speed response with PI for a step increase in load.

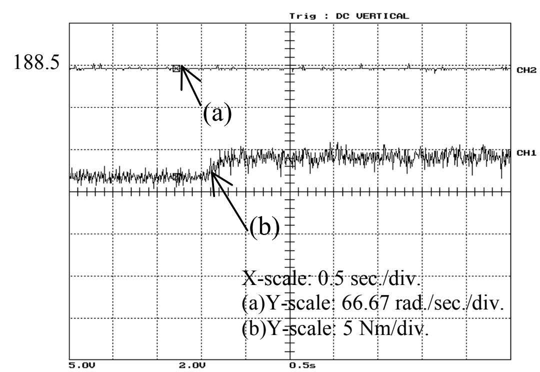

Fig.10 Experimental responses of the drive with GFLC for a step increase in load: (a) speed, (b) torque.

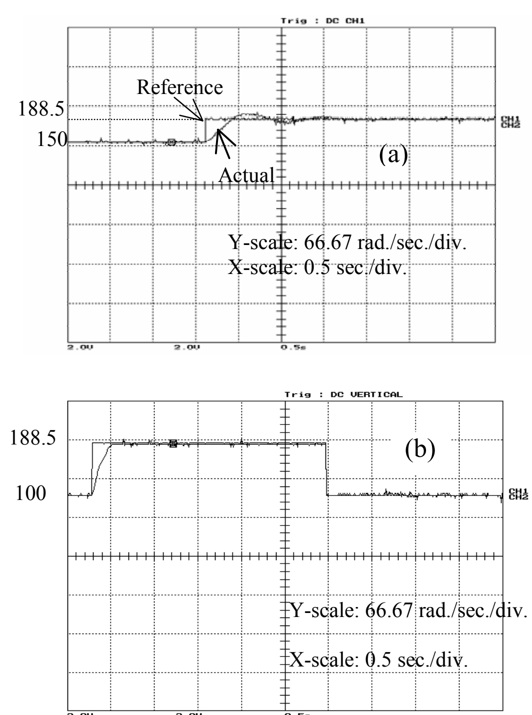

Fig.11 Experimental speed responses of the drive for a sudden change in speed: (a) PI and, (b) GFLC

validity of the proposed control technique has been established both in simulation and experiment at different operating conditions. In order to prove the superiority of the proposed controller a performance comparison with a conventional PI controller has also been provided. There is a close agreement between simulation and experimental results. The unique contribution of this paper is that the developed FLC scheme is very simple with only one or two membership functions for the input vectors and the output vector does not have any membership functions. This results in a low real-time computational burden and hence, found very effective in terms of speed tracking with disturbance rejection. The performance of the proposed GFLC based IPMSM drive system has been found more robust as compared to the conventional PI controller based system. Hence the developed GFLC is recommended for high performance industrial drive applications.

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